Distortion Product Otoacoustic Emissions in Normally Hearing Subjects

N. Pérez*, I. Ruiz de Erenchun, M. I. Olleta and R. García-Tapia

Departamento de Otorrinolaringología
Clínica Universitaria de Navarra
Facultad de Medicina
Universidad de Navarra
31080 Pamplona (Spain)

ABSTRACT

The finding of active function by the outer hair cells for sound processing prior to neural transduction in the inner hair cells represents the basic mechanism for the generation of Otoacoustic Emissions in the cochlea. Among them the so-called Distortion Product Otoacoustic Emissions represent a tool for an in depth knowledge of the Organ of Corti micromechanics, more advantageous than others, based on their properties, that makes possible an objective frequency-specific study: The response in a group of normally hearing subjects is presented and characterized to ascertain the basic features to be used in further testing of deaf people.

KEY WORDS

Cochlea, Hearing, Cochlear amplifier.

It was postulated 30 years ago that the sharp frequency selectivity exhibited by the cochlea was due to a double mechanism for sound transduction in which a process of mechanical-to-electrical transduction was coupled to an electrical-to-mechanical process (5). This hypothesis was never demonstrated until Kemp discovered that energy is emitted by the cochlea and registered in the ear canal as sound pressure level variation which he called Otoacoustic Emission (8, 9). It was subsequently proposed that such energy might be the by-product of the electromechanical converter which works in the cochlea as an amplifier of the stimuli delivered to the inner ear, so that non-linearities found in the cochlear function were easily explained.

The search for a «second amplifier» and generator of the response evoked by the cochlea was directed to hypothetic active mechanisms in the inner ear for sound analysis, which led to the redefinition and better understanding of some findings that point to the possible oscillatory motion of the Outer Hair Cells (OHC) in the Organ of Corti. Anatomical considerations are the existence of actin, myosin and tropomyosin in the stereocilia and cuticular plate of the OHC (4) and their attachment to the inferior aspect of the tectorial membrane (10). The innervation of the Organ of Corti supports the idea of a double system for signal analysis, so that the inner hair cells contribute to 90-95 % of the afferent pool in the auditory nerve while the efferent endings terminate in both groups of cells with a higher representation in the OHC (14). The effect that the exposition to intense noise, administration of ototoxic drugs and suppression contour obtained with the use of additional tones have on OHC and acoustic emissions was enough to assign a cochlear origin to these emissions. Finally, the experimental observation of the electromotility of the OHC produced evidence that they generated the Otoacoustic Emissions (2) or that they were at least one of their most relevant factors.

In the peripheral auditory system the OHC words as an amplifier of the movement of the basilar membrane (travelling wave) induced by the sound transmitted to the oval window. In a very specific point, tonotopically situated along the cochlea, the displacement of the Organ of Corti produces a relative motion between the tectorial membrane and the reticular lamina and the deflection of the cilia of the OHC that induces its depolarization, originating a movement of consecutive elongation and shortening of the cell.

This activity augments the amplitude of the wave, which makes possible the depolarization of the inner hair cells due to a similar phenomenon of ciliary displacement creating, thus, a change in their resting potential. This is propagated to the banal pole of the cell where it induces the release of certain chemical transmitters that diffuse across the synaptic cleft to activate postsynaptic receptors at the afferent ending of the auditory nerve with enough intensity to generate an action potential. In this model the olivocochlear efferent system plays an inhibitory role by reducing the contractil movement of the OHC so that it limits the stimulation of the inner cells. The mechanical modulation done by the OHC is backwardly transmitted through the basilar membrane to the oval window, stapes, ossicular chain, tympanic membrane and is registered in the ear canal.

The existence of distortion or intermodulation products is related to the non-linear function of the inner ear in sound processing and it is easy to observe different distortion products as harmonics, precisely defined by mathematical formulae, after the stimulation of the system with any combination of tones, also called primaries. In humans the most prevalent distortion product is that found at $2F_1$-F_2 and it has been studied by psychoacoustic means (6), registered in the auditory nerve in single fiber recording as cochlear microphonics (3). More recently, with the advent of systems for the study of otoacoustic emissions, it has been possible to study them in the acoustic domain (7) and to use them for the diagnosis of sensorineural hearing loss (11).

The study of the prevalence of the DPOAE and their characteristics in a group of normally hearing subjects is the aim of our work.

MATERIALS AND METHODS

Subjects

Recordings were obtained from a total of 42 ears from 21 subjects (10 women and 11 men) with an age range from 21 to 30 years (mean = 26). The criteria for normal-hearing was based on normal otoscopic findings, pure-tone audiometric threshold of 10 dB hearing level or less, at octave frequencies between 0.25 and 8 kHz, intelligibility threshold for spondees words of 10 dB hearing level or less and normal middle ear pressure evaluated by means of tympanometry and stapedius muscle reflex threshold. No one of the subjects reported personal histories of ototoxic drug ingestion, ear infections, long-term noise exposure or a family history that included known hereditary deafness.

Method

Signal generation and response analysis are controlled by a computer system (VIRTUAL 330) installed in a Macintosh IIci. Two continuous primary tones (F_1, F_2) are generated and attenuated separately by a two-channel frequency synthesizer and delivered independently to a pair of insert earphones being mixed acoustically in the ear canal. In it the sound pressure is measured by a low-noise microphone system incorporated in the same probe where the tones are taken; this arrangement is sealed in the canal with an impedance probe protector. The F_2 to F_1 ratio (F_2/F_1) of the stimuli is kept constant at 1.21 and their intensity remains always the same ($L_1 = L_2$).

The microphone signal is delivered to a dynamic-signal analyzer for extraction of the Fourier components at the $2F_1$-F_2 frequency. To provide a measure of the level of the noise floor at which the measures are done, a Fourier analysis is also performed for the frequency 20 Hz below the emission frequency of the distortion product. If the response at $2F_1$-F_2 frequency is at least 4 dB SPL above the level of the noise a Distortion Product Otoacoustic Emission (DPOAE) is considered to be present.

DPOAE audiogram or DPgram is the representation of the DPOAE amplitude plotted at geometric mean of primary tones which represents the most probable place of the emission generation in the inner ear. The intensity of stimulation is 75 dB SPL and the number of pairs of primaries presented is 24, at 1/6 per octave between 500 Hz and 8810 Hz.

Input-output functions are done with primaries varying from 918 Hz to 8810 Hz so that their geometric mean represents auditory frequencies 1, 2, 3, 4, 6 and 8 kHz; equilevel stimuli are delivered from 35 dB SPL to 75 dB SPL in 5-dB steps, so that an estimate of the growing pattern of the response as a function of the intensity of stimulation is obtained. In the frequencies just mentioned DPOAE-threshold is defined as the level of the primaries in which a DP emission is found.

RESULTS

All ears have been observed to have measurable DPOAE well above the noise floor of the recording system.

In figure 1 the response obtained with the use of primaries at 75 dB SPL is shown. DPOAE amplitude and noise floor are plotted at geometric mean of primaries, presenting the first one as mean ± 1 SD and the second as the mean + 1SD, so that the significance of the response is incremented due to the evaluation of the acoustic emission in relation to the highest level of noise. This and the study of its growing pattern referred to below points at the biological origin of the emission evoked, which is not an artifactual harmonic due to the peculiar resonant properties in the ear canal.

The results indicate the existence of two dips in the amplitude function at 3 kHz and 6 kHz unaccounted by the change in the system noise; overall the amplitude remains constant throughout the frequency domain, ranging from 5 to 30 dB SPL above noise floor closely dependent on the frequency of study. Otherwise noise floor is of very low intensity due to the proper placement of the subject under study inside an acoustically insulated room as well as to the process of repetitive acquisition of the signal and averaging.

In figure 2 average I/O functions collected at the 6 individual frequencies are shown. Detection threshold is situated at 35-40 dB SPL across frequency and dynamic ranges vary between 30 and 45 dB SPL. The growing pattern is non-linear at intensities of stimulation lower than 55 dB SPL, which is most prevalent in lower frequencies. All these results depend greatly on the frequency of study.

DISCUSSION

The fact that DPOAE testing allows the study of the micromechanics involved in sound processing by the peripheral auditory system in the Organ of Corti (13), constitutes its most important feature.

The primary purpose of the present study was to collect information from normally hearing subjects to ascertain the characteristic of the response and parameters for further testing and identification on inner ear deficiencies in patients. There is no doubt that Otoacoustic Emissions represent a potential tool for the evaluation of the physiological status of the cochlea with no interferences from the central auditory system or from the external and middle ear, being classified according to the stimulus that evokes the response. Spontaneous otoacoustic emission (SOAE) is the narrow band acoustic energy generated naturally within the cochlea when no stimulus is present; transiently evoked otoacoustic emissions (TEOAE) are defined as the acoustic energy elicited by presenting brief stimuli to the ear, while distortion product otoacoustic emissions (DPOAE) are the acoustic energy elicited by presenting two tones simultaneously to the ear.

In close agreement with other studies several features are important for the identification of the response. The prevalence of 90 % to 100 % in normally hearing subjects was first precluded by KEMP (9) and observed by LONSBURY-MARTIN et al. in adults (11), and by BONFILS et al. in neonates (1). The amplitude of the response is similar to that found by others (11, 13). Average I/O functions display some important properties such as dynamic range of 30 to 45 dB SPL (11, 12), detection threshold within 10 dB SPL centered at 35 dB SPL (11, 13) for all frequencies, and differences in growing function for frequencies and level of stimulation (1).

Unlike other authors we found two dips in the amplitude of the response at 3 and 6 kHz. The first one, also observed by others (11), is displaced toward the lower frequencies as the intensity of stimulation increases and is probably related to an interaction of resonances in the ear. The high frequency dip, usually not found by other authors is due to an attenuation of the response by the middle ear transfer function.

The presence of the evoked emission in all normally hearing subjects indicates that a particular property of the inner ear necessary for its correct function is being explored so that its absence call for further study to locate the origin and type of lesion.

As a test for hearing impairment evaluation, the following characteristics of the response are noteworthy. High sensitivity, in as much as the evoked emission has an audiometric threshold situated well below the psychoacoustic. On the other hand the dynamic range is wide enough for changes to be considered in the behavior of the growing function, accounted by subtle changes in the morphological integrity of the cochlea. As a practical development this is considered to be an objective test, so that the subject does not interfere voluntarily with the signal or has to be aware of the level at which the stimuli elicit the desired response. This is of great importance for the screening of hearing dysfunction and testing of difficult-to-test subjects.

Pre-neural origin of the response makes possible to separate the sensorial subset in mixed lesions of the peripheral auditory system. This attribute is enhanced by the outer hair cell specificity of the evoked otoacoustic emission, which is uniquely frequency-specific with the DPOAE, so that a tonotopic diagnosis of sensorineural hearing loss (ototoxicity, presbyacusis, congenital genetic deafness) can be had in terms of site of the lesion (neural vs. sensorial), mechanism of cochlear transduction involved (active vs. passive) and frequency pattern of hearing loss or inner ear location of the damage.

Another very appreciated characteristic is noninvasiveness related to patient comfort and absence of interference with physiological properties of the external and middle ear for sound transmission.

All these properties render this test highly valuable for hearing assesment, and future work should be conducted for the evaluation of its specificity and sensitivity for hearing loss detection in different clinical entities.

RESUMEN

La actividad mecánica de las células ciliadas externas, responsable de la transducción pre-neural del sonido, representa uno de los generadores de Otoemisiones Acústicas. De éstas, las Otoemisiones Acústicas de Productos de Distorsión representan un sistema nuevo para la valoración de la situación del Organo de Corti basado en la función micromecánica coclear inherente a las distorsiones creadas por la onda viajera y permiten una valoración tonotópica y objetiva. Se presenta la respuesta en un grupo de sujetos normo-oyentes que permite conocer los parámetros básicos que sirvan para compararlos con los resultados de sujetos con lesiones del oído interno manifetadas por hipoacusia.

Palabras clave: Cóclea, Audición, Amplificador co-clear.

REFERENCES

1. Bonfils, P., Avan, P., Francois, M., Trotoux, J. and Narcy, P.: *Acta Otolaryngol. (Stockh.),* 112, 739-744, 1992.
2. Brownell, W.E.: *Ear Hear.*, *11*, 82-91, 1990.
3. Dallos, P., Schoeny, Z. G., Worthington, D.W. and Cheatham, M.: *J. Acoust. Soc. Am.*, 46, 356-361, 1969.
4. Flock, A., Cheung, H. C., Flock, B. and Utter, G.: *J. Neurocytol.*, 10, 133-139, 1981.
5. Gold, T.: Proc. R. Soc. Lond. B. Biol. Sci., 135, 492-498, 1948.
6. Goldstein, J. L.: J. Acoust. Soc. Am., 41, 676-689, 1967.
7. Harris, F. P., Lonsbury-Martin, B. L., Stagner, B. B., Coats, A. C. and Martin, G. K. :J. Acoust. Soc. Am., 85, 220-229, 1989.
8. Kemp, D. T.: J. Acoust. Soc. Am., 64, 1386-1391, 1978.
9. Kemp, D. T.: Arch. Otorhinolaryngol., 224, 37-45, 1979.
10. Kimura, R. S.: Acta Otolaryngol. (Stockh.), 61, 55-72, 1966.
11. Lonsbury-Martin, B. L., Harris, F. P., Stagner, B. B., Hawkins, M. D. and Martin, G. K.: Ann. Otol. Rhinol. Laryngol., Suppl 236, 3-14, 1990.
12. Probst, R., Antonelli, C. and Pieren, C.: In «Cochlear mechanisms and otoacoustic emissions». (Grandori, F., Cianfrone, G. and Kemp, D. T., eds.) Karger. Basel, 1990. pp. 117-125.
13. Probst, R., Lonsbury-Martin, B. L. and Martin, G. K.: J. Acoust. Soc. Am., 89, 2027-2067, 1991.
14. Spoendlin, H.: In “Ultrastructural Atlas of the Inner Ear”. (Friedmann, I. and Ballantyne, J., eds.), Butterworths. London, 1984. pp. 133-164.

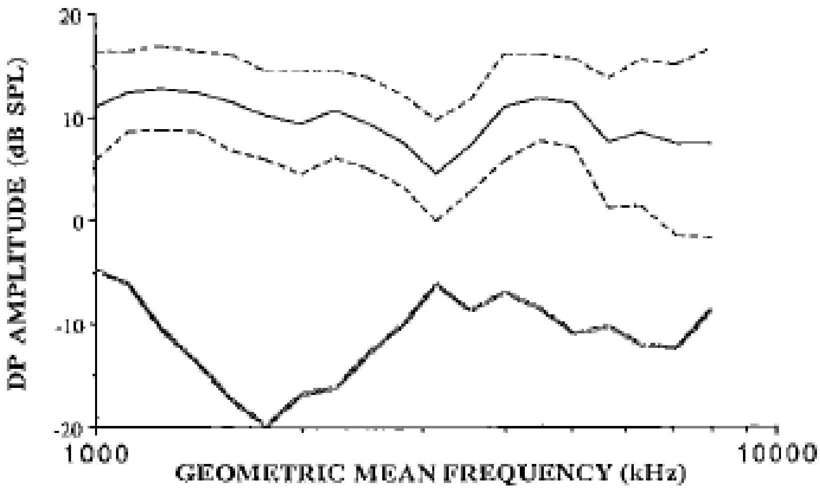

Figure 1. Distortion product emission (DPE) audio-gram.
Mean DPE amplitude ± 1 SD is presented as fine lines and noise floor plus 1 SD as solid line. They are plotted at geometric mean of primary tones to correspond to region of generation on basilar membrane; the intensity of stimulation is 75 dB SPL for $L_1 = L_2$

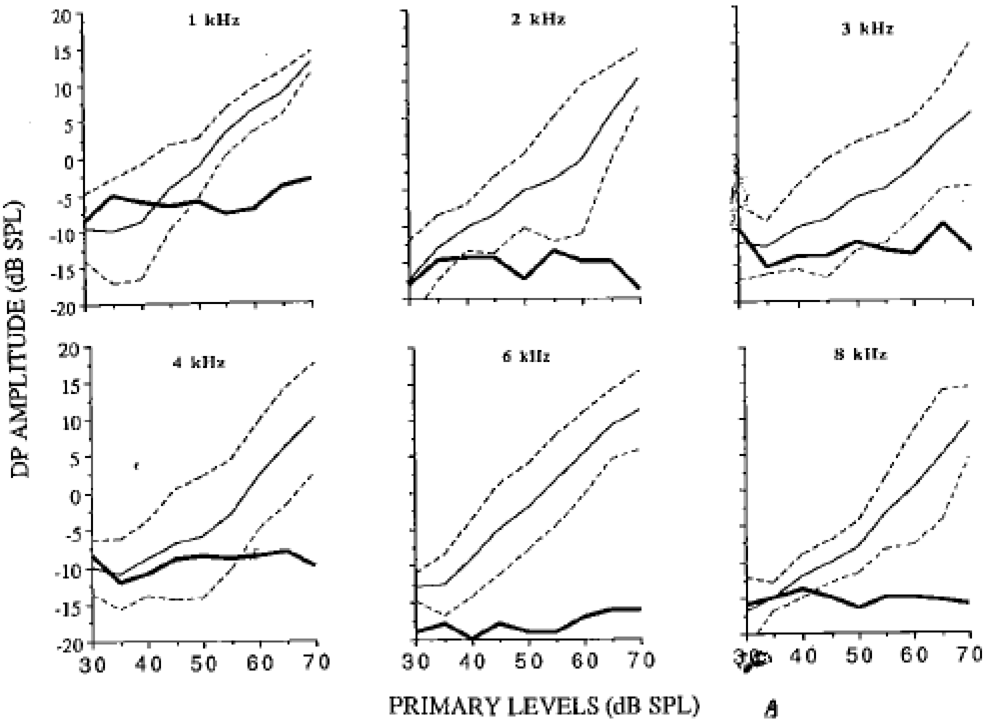

Figure 2. Distortion product emission (DPE) input-output functions obtained at six frequencies with equi-level primaries whose geometric means represent the frequency of study.
Mean DPE amplitude ± 1 SD is presented in fine fines and associated noise floors plus 1 SD as solid line.